EMPIRICAL AND THEORETICAL SEISMIC ENERGY PARTITIONING FROM EXPLOSIONS UNDER DIFFERENT CONFINEMENT AND MEDIA CONDITIONS

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ABSTRACT

Some of the data-analysis results from the 2003 Arizona Source Phenomenology Experiments (SPE) were unexpected—explosions in slow-velocity limestone appear to be mainly isotropic under most emplacement conditions, while explosions in higher-velocity granite porphyry are marked by interesting source anisotropy. Even though the emplacement media were different, we did not expect to observe such prominent differences in the explosion phenomenology. While the SPE project was successfully completed, important questions remain regarding the fundamental physical mechanisms behind these differences, which could have important implications on explosion-generated *S*-wave models.

To improve our understanding of the physics behind the explosive-source phenomena, we are comparing the SPE data to that of other explosion experiments, including the Non-Proliferation Experiment (NPE). We are attempting to 1) develop a physical interpretation of the different SPE sources using comparative moment tensors analyses; 2) quantify the effects of spall, compensated linear vector dipole (CLVD), and other secondary sources; 3) characterize near-source, local, and regional *S*-wave phases, including prominent *SH* waves; 4) conduct moment tensor inversions of NPE explosions, including an overburied 177-kg calibration explosion, for comparison to the SPE explosions; and 5) examine the variability of regional phase partitioning from single-fired and production mining explosions in order to assess the transportability of regional discriminants. We have just started a two-year, multi-phase physical basis investigation aimed at developing a new explosion source model explaining the differences between the isotropic explosions in highly fractured limestone and anisotropic explosions in granite porphyry.

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OBJECTIVES

The 2003 Arizona SPE was conducted by Weston Geophysical, Southern Methodist University (SMU), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and the University of Texas at El Paso (UTEP). The experiment included dozens of delay-fired mining blasts and 19 single-fired chemical explosions recorded by hundreds of seismic stations at local and near-regional distances. The single-fired explosions were detonated either in a *slow velocity, highly-fractured limestone* at a coal mine on Black Mesa, AZ or in a *faster-velocity granite porphyry* at a copper mine near Morenci, AZ. The results from prior research conducted by the SPE consortium are summarized in Table 1.

Table 1. Summary of results from the SPE explosions.

Analysis	Slow-velocity limestone medium	Faster-velocity granite porphyry
Moment Tensors	Isotropic under all confining conditions	Strong anisotropy under all confining conditions
***S*-wave Generation**	Large *SH* and direct *S*-wave arrivals with onset times that trace back to explosion origin times plus an offset	*S*-wave arrivals with onset times that trace back to explosion origin times
Single Shot Regional *P/S* Discrimination	Easily classified as explosions in 6-8 Hz *Pg/Lg*	Overlap with earthquakes for 6-8 Hz *Pg/Lg*
Mining Blast Regional *P/S* Discrimination	Classified as explosions, but separation from earthquakes is smaller than single-fired shots; Large variance between blasts	Classified as explosions with separations from earthquakes larger than single-fired shots; Large variance between blasts

The 1993 NPE was conducted by the Department of Energy (DOE) and examined chemical-nuclear equivalence by detonating a kiloton of single-point, fully contained chemical explosives at the Nevada Test Site (NTS). When compared with nearby nuclear tests, the regional seismic records were found to be essentially identical, other than a different chemical/nuclear amplitude-yield scaling factor (e.g., Denny et al., 1997). Regional discriminants classified the NPE as a nuclear explosion (Walter et al., 1995). An additional highly over-buried NPE calibration explosion (NPE Cal) of 177 kg detonated at 390 m depth provided data from a source with no free surface non-linear interaction for comparison with the much larger NPE and its free surface interaction. The comparison of these two NPE shots could provide insight into possible depth of burial effects in the SPE data set.

Even though the SPE project was successfully completed, interesting phenomena arose from the analyses, and important questions remained. In this paper, we present initial work on answering many of these questions, including:

- Why are the source characteristics different for limestone and granite porphyry?
- What are the generating mechanisms of the larger vertical component and strong off-diagonal component(s) noted in the moment tensors of the Morenci copper mine explosions? Block motions? Asymmetries in damage? Can they be modeled with a compensated linear vector dipole (CLVD, Knopoff and Randall, 1970) source?
- What are the effects of the off-diagonal energy in the moment tensor on the generation and propagation of S waves?
- Can the scattering of *Rg* be isolated and the contributions to *S* waves quantified?
- Can near-source moment tensor investigations of the NPE and its highly over-buried calibration shot provide further constraints on depth-of-burial effects?
- Can a source model be developed for both SPE emplacement media so that both local and regional data can be explained?
- Can we explain the variance in the *P/S* ratios for the SPE shots and mine blasts at regional distances based on mining explosion practices/confinement/scaled depth of burial/etc?

RESEARCH ACCOMPLISHED

Comparison of Moment Tensors

We have compared the moment tensors for two under-buried SPE explosions at Black Mesa and Morenci (Figure 1). The results show that the absolute amplitudes and signal characteristics for these similar yield and depth explosions were almost the same on the M_{zz} component. While the M_{xx}, M_{yy}, and M_{zz} components for the Black Mesa shots are almost identical to each other, we note that the M_{xx} and M_{yy} components for the Morenci shot are greatly reduced compared to the corresponding M_{zz} component. In fact, they are of similar amplitude to the off-diagonal component M_{xz} for this shot. Conversely, there is no significant energy on the off-diagonal components for the Black Mesa shot. The explanation for these differences might be in the damage phenomenology as the Morenci shot cratered while the Black Mesa shot had a symmetric rubble mound (often called retarc, or crater spelled backwards). Another possible explanation is the different fracture generation and propagation phenomena that could result in different moment-tensor representations. We are continuing to examine near-source data from both mines to infer possible effects of fracture generation and propagation.
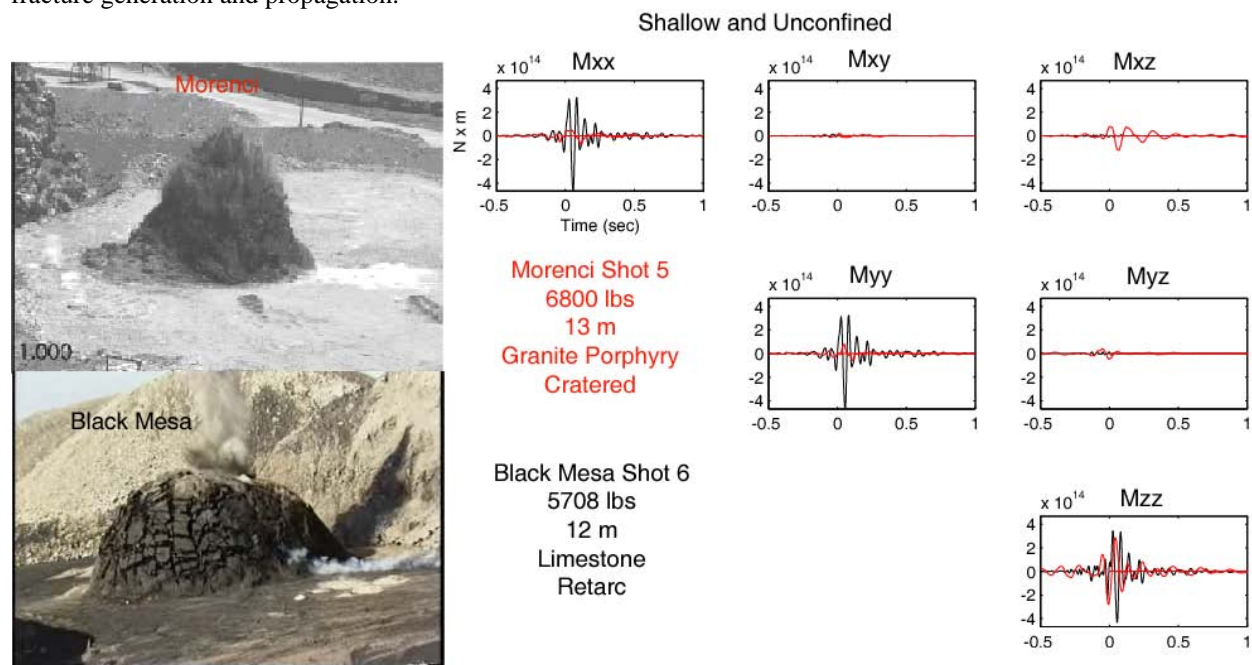

Figure 1. Comparison of surface damage and moment tensors for two SPE explosions in different lithologies.

Examination of Spall

Spall is defined as the tensile failure of the near surface layers (Eisler and Chilton, 1964; Stump, 1985). For a contained explosion, the initial compressive shock wave reflects off the free surface as a tensile wave, which causes subsurface strata to fail in tension. Spall has been represented as a cylindrical source delayed in time from the explosion (Stump, 1985) or as a circular horizontal tension crack that opens and closes in the vertical direction (Stevens et al, 1991). To model the SPE explosions, we are extending the definition of spall to include both vertical and horizontal material cast.

Spall may have played an important role in the moment tensors for the unconfined SPE shots detonated near a free face (referred to as cast shots because the material was "cast" into the pit below). The cast shots have more complicated moment-tensor time histories (Figure 2). In addition, their moment tensors show an enhanced low-frequency (1-6 Hz) signal in the off-diagonal components, particularly in M_{yz}. This signal may have resulted from the material cast or horizontal spall effects.

We are working to quantify the effects of spall at both test sites using a forward modeling approach. Our emphasis is on modeling the data and moment tensors of unconfined near-free-face explosions and quantifying the contribution

of spall to the near-source seismic wavefield and to the generation of shear waves, especially *SH* waves, from these explosions. The depth of the equivalent spall source is not the same as the initial isotropic component of the explosion since the non-linear failure of the material dominates in the region above the contained explosion. In order to assess these effects on empirically determined moment tensors, we are conducting a forward modeling and inversion study.
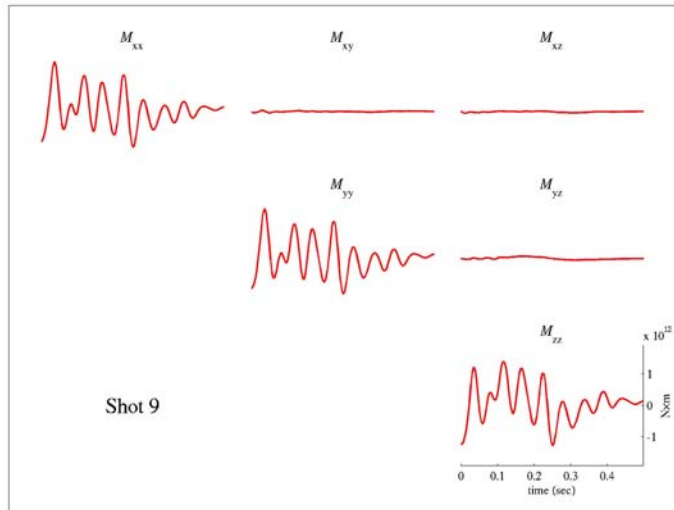
Figure 2. Moment tensors from the inversion of a 1480-kg cast explosion at the Black Mesa coal mine. When compared to the moment tensor of an unconfined shot (such as in Figure 1), we note that the cast shot detonated near a vertical free face exhibits oscillatory behavior and low frequency energy on the off-diagonal M_{yz} component.

Rg from a CLVD

It has long been recognized that underground explosions excite *Rg* waves efficiently. However, explosions in the field are not simple monopole (point isotropic) sources; rather, they are distributed sources in time and space, and emit non-spherical wave fields. Patton and Taylor (1995) proposed that the mechanism of *Rg* waves might involve a compensated linear vector dipole (CLVD, Knopoff and Randall, 1970), where the CLVD is the elastodynamic equivalent of an inverted conical volume source with its apex at the detonation point. The medium inside the cone deforms and fails as a result of tensile stresses caused by the downgoing shock wave reflected off the free surface. Spallation, which usually involves shallow, poorly-coupling geologic strata that open and close with no net displacement, is an example of such failure. Another example is driven block motions at depth, as envisioned by Masse (1981). This source might be more important for seismic wave generation than spall if it involves permanent deformations and couples better into the ground, since its centroid is located in more competent rock at depths greater than spall.

The source excites azimuthally independent Rayleigh waves and does not excite Love waves. Several interesting features characterize the Rayleigh-wave radiation from such a source, including excitation nulls in the Rayleigh spectra, which occupy the frequency range of *Rg* waves for source depths in the upper 300 meters of the crust. We generated *Rg* synthetics for a monopole ($M_{xx}=M_{yy}=M_{zz}=1$; $M_{xy}=M_{xz}=M_{yz}=0$) at 30 meters depth in the Morenci and Black Mesa velocity structures. We then generated *Rg* synthetics for a CLVD ($M_{xx}=-0.5$ $M_{yy}=-0.5$ $M_{zz}=1$; $M_{xy}=M_{xz}=M_{yz}=0$) source in the same structures at 20 meters depth (2/3 of the explosion centroid). The spectra for the *Rg* synthetics are shown in Figure 3 with CLVD excitation nulls at 4 Hz for the slower velocity structure and 7.5 Hz for the faster velocity structure. It appears that there is an excitation null between 2 and 4 Hz in the observed data from a 25-meter deep SPE shot at Black Mesa, but we do not observe a null in a 33-meter deep explosion at Morenci. We note that the Morenci synthetics suggest the null would be just outside our observed *Rg* frequencies, though.

A more detailed and thorough modeling study of the SPE data from the copper and coal mine single-fired explosions is being completed to determine if the CLVD source was a significant component of these explosions. To complete this task, we are using the methods defined by Patton et al. (2005) to match the amplitude and phase of a combined

monopole + CLVD source to the observed data. By determining the static moment for any CLVD source, we will have an important parameter needed for modeling the seismograms at regional distances.
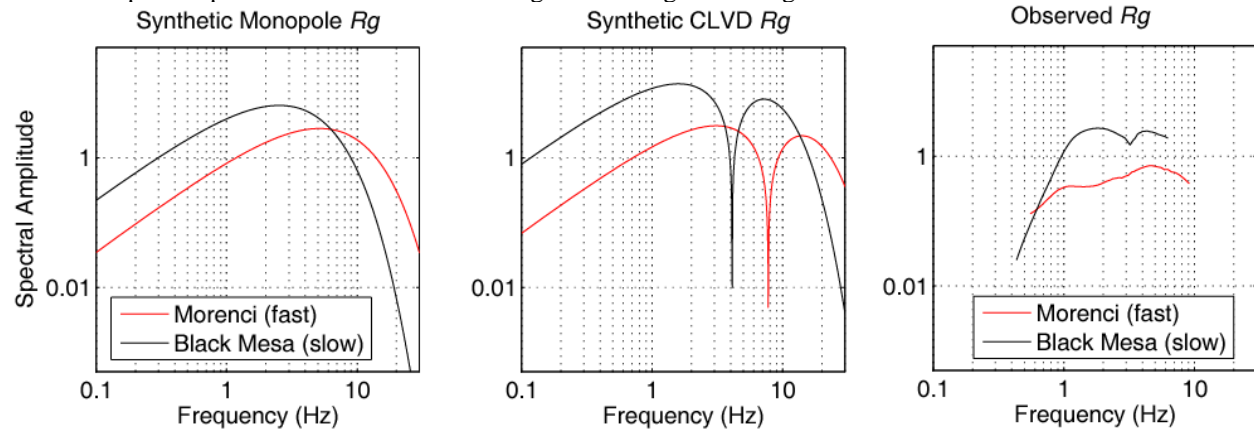
Figure 3. Spectra for *Rg* generated from a synthetic monopole (left) in the velocity structures determined for Morenci (red) and Black Mesa (black). Also shown are the spectra for a synthetic CLVD source in the same media (middle) and the observed *Rg* spectra (right) for the deepest SPE shots.

Shear Wave Generation

All available data from near-source, local, and near-regional distances are being combined in our analyses to quantify the shear wave generation and explain the origin of observed shear waves in different media. For the explosions in a granitic body, the shear energy includes both the direct shear arrivals and *Rg* at the local and near-regional distances recorded by the single-channel digitizers known as "Texans." The record sections presented in Figure 4 are from a 5076 kg Morenci shot, and have a frequency range of 0.7 to 20 Hz (Figure 4a) and 0.5 to 3 Hz (Figure 4b). The *Rg* energy is strongest at the lower frequencies, while the *P*-wave amplitudes are much larger than the shear amplitudes at high frequencies. There is significant shear energy with arrival times that are traceable back to the origin time.
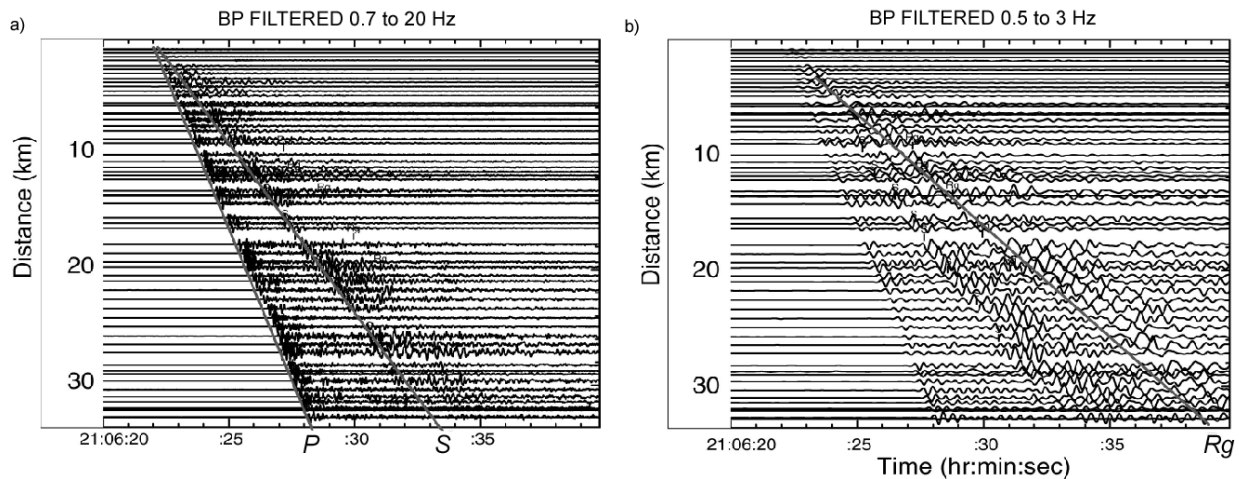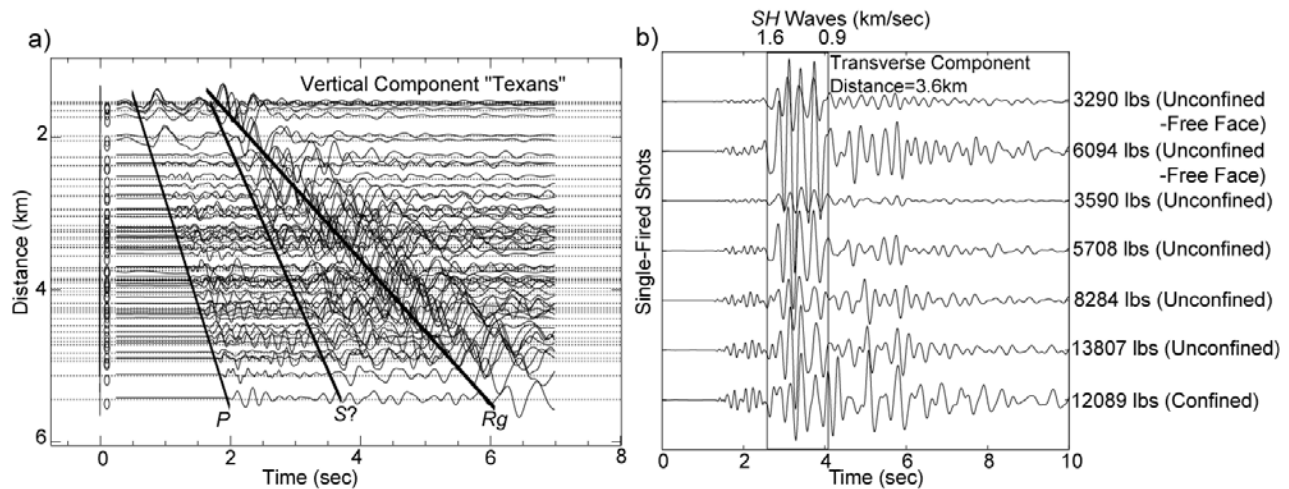

Figure 4. Phase arrivals from SPE shots at the Morenci copper mine. a) Record section of Texan recordings showing *P*- and *S*-wave arrivals. b) Record section filtered to highlight the short-period Rayleigh waves (*Rg*).

The SPE shots in limestone also generated significant shear-wave motion, as evidenced in Figures 5a and 5b. On the vertical-component "Texan" recordings (Figure 5a), the *P*-wave and *Rg* arrivals are easily identified and are traveling at apparent velocities of 2.7 km/s and 1 km/s, respectively. There are additional arrivals that we delineate

in the figure as possible direct *S*-wave arrivals. The apparent velocity for the phase is ~1.8 km/s. However, we note that tracing the arrival times of this phase back to the origin results in ~1 sec of offset from zero. Some may attribute this delay to near-source scattering, while others may argue that the delay is caused by secondary source effects (e.g., spall or CLVD).
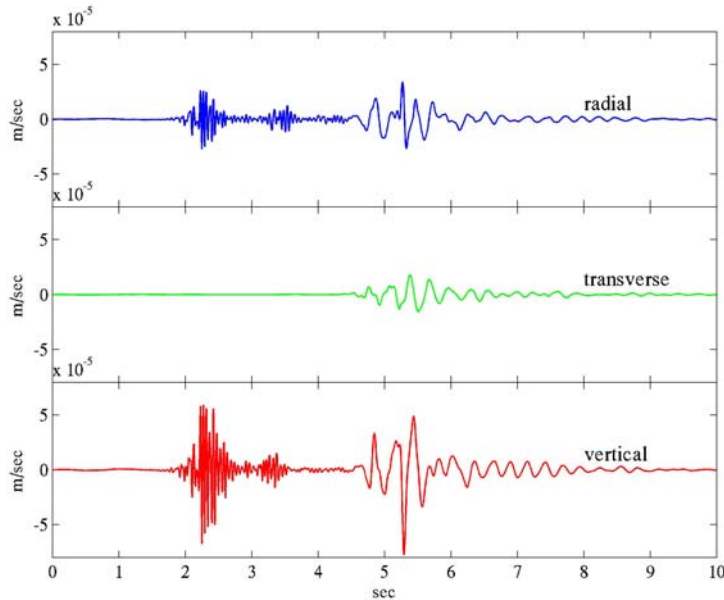
Large amplitude *SH* waves were generated by the SPE explosions (Figure 5b). Similar arrivals have been noted in near-field recordings of nuclear explosions in Kazakhstan (Stevens, 2006) and chemical explosions in Alaska (Leidig et al., 2007). It is interesting to note that the largest amplitude *SH* waves are not associated with the largest yield explosions, but instead are observed in data from blasts in a topographic bench next to a free face.

Figure 5. Phase arrivals from SPE shots at the Black Mesa coal mine in northeastern Arizona. a) Record section of "Texan" recordings showing *P*, *Rg*, and a possible *S*-wave arrival. b) Transverse component recordings of seven SPE explosions at a single broadband station showing large amplitude *SH* (Love?) arrivals.

The moment tensors for a free-face shot were shown in Figure 2. Although the amplitude of the M_{yz} component in the 1–6-Hz frequency band is only a small fraction of the amplitude of the isotropic component in the same frequency band for the cast shots, it can generate large-amplitude shear waves. The deviatoric moment-tensor component of an explosive source, the causes of which include the non-spherical geometry of the source, the near-source region medium heterogeneity and/or anisotropy, and the secondary source effects such as CLVD and material cast can be important contributors in shear-wave generation even though the deviatoric component itself may be small. Synthetic seismograms (Figure 6) generated for the moment tensor results shown in Figure 2 show how small anisotropic behavior can generate strong *SH* waves.

Figure 6. Synthetic seismograms from the moment tensor shown in Figure 2. Receiver was 5 km from the source and at 0° azimuth from the *x* direction. Notice the large amplitude *SH* waves generated from this moment tensor solution even though the M_{yz} component was not very large (barely perceptible on Figure 2).

Numerical Modeling

We are using the detailed velocity and attenuation models derived from the original SPE project coupled with the moment tensors to conduct numerical modeling of recorded near-source, local, and regional seismograms. We are using 1D, 2D, and 3D models, and including topography and stochastic properties of the media in order to quantify possible scattering effects. The goal of this modeling exercise is to determine how much of the local data can be related back to source effects and what characteristics of the local and regional data are due to path effects.

We present preliminary modeling results from the Morenci copper mine. The model (Figure 7) was developed by Kim and Stump (2005) using surface wave inversions and *P*-wave raytracing. The source is located at the origin, although a buffer is placed around the edges of the model during the numerical computations. We computed synthetics for both isotropic and anisotropic explosions documented by the Morenci moment tensor inversion (e.g., Figure 1). The results for the latter are presented in Figure 8 (black) and are compared to observed (red) data. As is expected, we are modeling the onset of *P* and *Rg* very well from these models. It is also interesting to note that the relative amplitudes of *P* and *Rg* in this frequency band (0.5 to 4 Hz) are similar for the observed and synthetic data. When a purely isotropic explosion was used, the relative amplitude ratios were dissimilar due to larger-amplitude P waves.
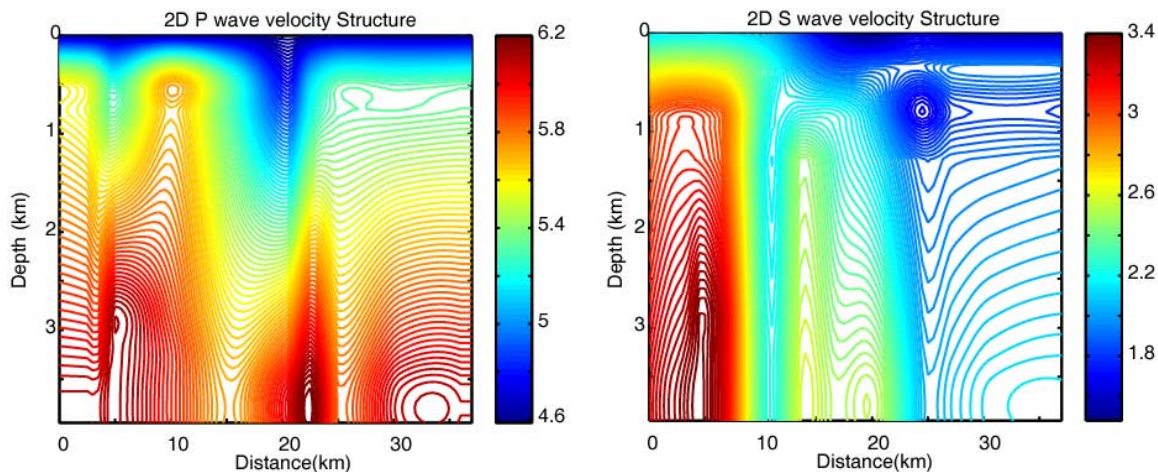
Figure 7. An example of upper crustal *P*- and *S*-wave velocity structures for the Morenci mine being used in the numerical modeling studies.
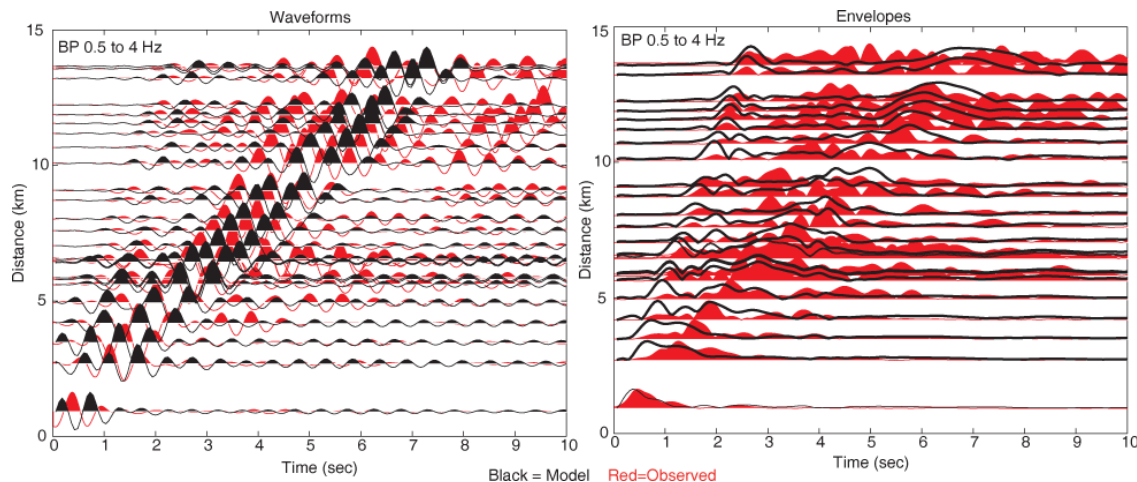
Figure 8. Preliminary 2D modeling results for the crustal *P*- and *S*-wave velocity model shown in Figure 7. Left graph) Waveforms show our synthetics match some of the observed waveform characteristics. The waveforms were filtered between 0.5 and 4 Hz. Right graph) Envelope functions for the observed (red) and predicted (black) waveforms.

CONCLUSIONS AND RECOMMENDATIONS

Explosions recorded during the SPE project in a slow-velocity medium appear to be mainly isotropic under most emplacement conditions, while explosions in a higher-velocity medium are marked by interesting source anisotropy. We are completing analyses to determine the cause of this anisotropy, such as a variation in the damage phenomenology. Synthetic seismograms generated from moment tensors indicate that a small deviatoric component may result in significant shear, particularly *SH*, energy.

We have also initiated studies examining the source of *Rg* and shear waves. Comparing observed *Rg* spectra to synthetic CLVD *Rg* source spectra illustrates that the CLVD source may have played an important role in the explosive source. A delay in the origin time of shear waves from the Black Mesa explosions points to a secondary source such as a CLVD, fracturing, or spall. Similar analyses will continue to be conducted on the NPE data and data from other explosive source projects to aid in development of a comprehensive explosive source model.

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